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Evolution of Hillslope Soils: The Geomorphic Theater and the Geochemical Play

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Abstract

How and how fast do hillslope soils form as the landscape's morphology changes over time? Here we show results from an ongoing study that simultaneously examines the morphologic and geochemical evolution of soil mantled hillslopes that have been exposed to distinctively different denudation history. In Northern Sierra Nevada, California, we are investigating a tributary basin to the Middle Fork Feather River. A major incision signal from the river is well marked in a knick point within the tributary basin which stretches from its mouth to the Feather River at the elevation of ~700 meter to the plateau at the elevation of ~1500 meter. Hillslopes are significantly steeper below the knickpoint. We are currently constraining the area's total denudation rates using cosmogenic radio nuclides, but the previous study suggested an order of magnitude differences in total denudation rates below and above the knickpoint. When compared with topographic attributes calculated from LIDAR data, physical erosion rates can be modeled as linear function of ridge top curvature. Surprisingly, over the wide range of total denudation rate, soil thicknesses do not vary significantly until a threshold point where soil mantled landscapes abruptly shifts to bedrock dominated landscapes. Bioturbation by tree falls appear to buffer soil thickness over the wide range of physical soil erosion rates. From three Hillslopes with different physical erosion rates, the concentrations of zirconium –which were considered conserved during dissolution and leaching – were determined and used as a proxy for the degree of mass losses via chemical denudation. There is a general trend that colluvials soils along the hillslopes with lower physical erosion rates are enriched in fine size fractions, Zr, and pedogenic crystalline iron oxides. Likewise, the saprolites show greater degree of chemical denudation at the sites above the knick point, presumably because of the saprolites' longer turnover time in the slowly eroding landscapes. In the two steep Hillslopes below the knickpoint, no significant or systematic topgraphic trends were found for soil geochemistry. However, soils show increasing Zr enrichment in the downslope direction in the hillslope above the knickpoint, which suggests a critical denudation rate beyond which soils' turnover time is too short to develop a geochemical catena. As we acquire detailed CRN-based soil production rates and catchment scale denudation rates, we will combine the data with a mass balance model to calculate the rates of chemical denudation and weathering in soils and saprolites along the denudation gradient.

1.1 Introduction

Hillslopes serve as an excellent platform to integrate the current progresses in low temperature geochemistry and landscape evolution at a mechanistic and quantitative level. Additionally, hillslopes could be studied as a basic unit of landscape where the upland to stream connections can be explicitly documented. In process geomorphology, stream incision at the base of a hillslope steepens the adjacent slope gradient, which leads to accelerated colluvial flux. Thus the hillslope soil thins and the bedrock conversion to soil accelerates, which eventually drives the hillslope morphology toward a new steady state (Fernades and Dietrich, 1997). Our goal is to understand how chemical denudation (mass losses via dissolution and leaching), chemical weathering (conversion and production of minerals), and biological nutrient uptakes fit into this series of chain reaction. Given that the biogeochemical processes drive the geochemical evolution of soils, our study has equally significant bearing to the formation of hillslope soills.

While incorporating biogeochemical processes into the geomorphic evolution of hillslopes, there has been ambiguity in defining soils. In most of studies of soil mantled hillslopes that focus on the generation and transport of colluvial sediments, physically mixed layer has been generally equated with soils. However, this constraint has been recently extended to include saprolite as an integral part of chemical weathering (Dixon et al., 2009; Anderson et al.,2002), and these studies have exposed the chemical dynamics of saprolite as one that may affect not only its water holding capacities but also its breakability to the overlying soils (Burke et al., 2009). Taking these new challenges, this study also attempts to couple the weathering processes of saprolite with the geochemical and geomorphic evolution of soil mantled hillslopes.

We focus on three soil covered hillslopes that have experienced different levels of channel incision rate at their bases. The hillslopes are located within a tributary basin that has been adjusting to the major incision at the Middle Fork Feather River. One of the three hillslopes, POMD, is located above the knickpoint, while the two others are adjacent to (FTA) and below (BRC) the knickpoints, respectively (Fig. 1). Hillslopes below the knickpoint are significantly steeper. The hillslopes are sufficiently close to each other to ensure constant climate and vegetation, and the entire tributary basin is underlain by a homogeneous tonalite. The only difference between the hillslopes is the physical erosion rate.

Using these hillslopes as a natural laboratory, we address the transient sediment flux and chemical denudation rates on the soil covered hillslopes, and their combined effects on geochemical and geomorphic evolution of hillslopes.

1.2 Results and Discussion from Ongoing Works

1.2.1 Total denudation rate

Previous workers have used catchments' averaged slope gradient as a topographic indicator of erosion rate. In rapidly eroding landscapes (<~0.2mm/yr), however, there is no relationship between slope and erosion rates, yet our simulations showed that ground surface curvature continues to increase with physical erosion rates. Particularly, it was found that hilltop curvature is linearly proportional to physical erosion rates in Feather River basin. In this study, this relationship will be used in scaling up the physical erosion rates (ie the difference between CRN-based total denudation rates and geochemistry-based chemical denudation rates) to the entire tributary basin.

1.2.2 Extracting transient erosion rates from landscapes

While relationships between physical erosion rates and landscape attributes are needed for spatial scaling, our ability to constrain the past history of physical erosion rates is also required to understand the transient response of chemical denudation and weathering to tectonic forcing. Using a numerical model of hillslope evolution, we are currently constraining mostly likely history of physical erosion rates that have produced the present landscapes in the Middle Folk Feather River.

1.2.3 Soil thickness along an erosional gradient

In rapidly eroding landscapes, soils are assumed to be thin, whereas in slowly eroding landscapes soils tended to be thicker. Therefore, we expected that soil thicknesses would increase in the order of BRC, FTA, and POMD. According to the previous study in the area, there is about 15 fold increase in the total denudation rate from POMD toward BRC (Riebe et al 2000), which agrees with our LIDAR based analysis of hilltop curvature. More detailed rates of total denudation will be available as our ongoing CRN analysis is completed.

Surprisingly, there is little difference in soil thickness between the hillslopes (Fig. 2a). This led us to hypothesize that trees – which appears to derive soil production at the site – are capable of maintaining their rooting media (ie., colluvial soil) over a large range of soil erosion rates. Ongoing analysis of in-situ CRN analysis of samples from soil-saprolite boundaries may reveal a biological control of geomorphic evolution that is much tighter than previously considered.

1.2.4 Soil texture and particle size distribution along an erosional gradient

Instead of soil thickness, the soils' mean particle sizes are positively correlated with total denudation rates. The mass fractions of fine particles (<2mm) in soil samples are greatest in POMD (Fig. 2b). Within the fine size fractions, the mean particle sizes do not significantly differ between BRC and FTA. The mass percentages of larger rock fragments (>10 mm diameter), however, show significant and consistent increase from POMD to FTA and to BRC (data not shown).

1.2.5 Soil elemental chemistry trend with erosion gradient

Zirconium and rutile (TiO_2), which are conserved during chemical erosion, exhibit greater concentrations in the POMD soils (Fig. 3a), which indicates that the greatest degree of mass loss via dissolution and leaching has occurred in the POMD soils. They reveal surprisingly little difference between the soils from FTA and BRC, which agrees with the similar contents of fine size particles in the soils of FTA and BRC (Fig. 2b).

The increase in soil turnover time (set by differing physical erosion rates) from BRC to FTA appears to be enough to accumulate significant fine size fractions in the soils by physical breakdown without involving Zr-enrichment in the fine and coarse size fractions. However, the difference in the soil turnover time between BRC and FTA is not sufficiently long to produce significant amounts of clays and greater enrichment of Zr and TiO_2 via chemical dissolution and leaching. Such accumulation only occurs as the soil turnover time further increases with reduced erosion rates, as seen in POMD.

1.2.6 Emergence of geochemical soil catena

Topographic variation of soil elemental chemistry is significant and systematic *only* at the POMD (Fig. 3b). POMD has the lowest erosion rate. Thus there appears to be a critical physical erosion rate (and thus soils' turn over time) that is required for the formation of geochemical catena.

Within the eroding part of POMD transect, Zr enrichment in soils increases in the downslope direction. This reflects dissolution and leaching of elements as the collvial soil migrate in the downslope direction. This trend, however, does not continue in the depositional hollow where the soil is least enriched in Zr. This is likely due to the difference in sediment transport processes in the eroding vs. depositional areas. In the convex slope, tree throw appears to be largely responsible for sediment transport, and this process does not sort particle sizes. In the hollow, however, overland flow may occur and preferentially remove silt size particles enriched in Zr. The particle size data shows that the depositional soil has the highest amount coarse and clay particles that tend to survive the removal by overland flow (Fig. 3c).

1.2.7 Saprolite chemical weathering

The fraction of mass loss via chemical denudation relative to the initial parent material can be calculated using τ values ($\tau = [Zr]_r/[Zr]_s-1$) (Fig. 4). Negative τ values indicate mass losses. The more negative is the fractional mass loss in the saprolite, the less the τ values in the soils (Fig. 4). Similar results were found along a climate gradient in the Southern Sierra CA (Dixon et al., 2009). Our results, however, provide insights on how total denudation (instead of climate) affects the coupling between saprolite and colluvial soil via chemical weathering. In FTA and BRC experiencing greater physical erosion rates, there is indeed negative relationship between the soils' and saprolite's τ values. Therefore for a given duration of soil turnover time, soils that started with materials that had lost significant amount of weatherable minerals may lose less mass via chemical denudation. Several POMD soils have more negative τ values than the soils of other transects at similar τ values of saprolite. This is probably due to the longer turnover time of the soils at the POMD. It is also notable that saprolite at the POMD have more negative τ values with a narrower range, which might be also because of the longer turnover time of the saprolite at POMD.

1.2.8 Iron extraction chemistry

Pedogenic crystalline iron oxides (defined as the difference between dithionite-citrate extractable iron and sodium pyrophosphate extractable iron) have been shown to accumulate in soils as soils age. Such accumulation also occurs within the range of soil turnover times in the Feather River Basin (Fig. 5). Secondary iron oxides may inhibit the dissolution of primary minerals that they coat (White et al., 2003). The significance of this feedback in the erosion gradient is worthwhile to study particularly considering the assertion that chemical denudation may be limited by mineral supply which is equivalent to the statement that chemical dissolution may be lower in the soils with longer turn over time. Therefore, the iron oxide coating may compete with the soils' turnover time in reducing chemical dissolution rate of minerals.

1.3 Conclusion

In Feather River Basin, as soil mantled hillslopes adjust to increased level of channel incision rate at their bases, tree growth and falls appear to be capable of maintaining the soil thickness. However, due to the shortened turnover time of the colluvial soils, relative enrichments of fine size fractions, weathering conservative elements, and pedogenic crystalline Fe oxides decline in the soils. Adding on to this general observation, chemical denudation of saprolite functions as another limiting factor. In the hillslopes with lower physical erosion rates, the colluvial soils do not show that their enrichments of fine fractions and weathering conservative elements linearly increase with the increasing soil turnover time. This might be because the soils began to form from saprolite that had already lost most weatherable minerals due to their own longer turnover time.

Our ongoing works have three foci at this point. First, the turnover time of the colluvial soils is being constrained using cosmogenic radio nuclides. Second, numerical modeling is under way to constrain the past physical erosion rates within the studied tributary basin. Third, we are gaining stronger grips of the particle size distribution in the soils and sediments along the streams.

These ongoing works, in combination of the results presented here, will lead us to understanding how and how fast channel incision propagates upslope in terms of both physical and chemical denudation and weathering. This is a key to quantifying the tectonic control of chemical weathering, which is considered as one of prime mediators of atmospheric CO_2 level over geologic time.

This project has another important bearing with soil carbon cycle. Over the past decades, biogeochemists arrived at a broad consensus that organic matter, when associated with minerals (eg., adsorption on mineral surfaces or physical occlusion in aggregates), tend to be better protected from microbes and thus have longer turnover times. This coupling provides a pathway to integrate soil carbon cycle with landscape evolution. For example, in this study, pedogenic iron oxides have high specific mineral surface area, which may lender them to adsorb significant amount organic matter and thus stabilize them per gram basis. Therefore, the POMD soil may store more amount of carbon in mineral complexed forms than the soils in FTA and BRC (Fig. 4). In another level, the storage of organic carbon in soils should be negatively affected by the presence of coarse materials like boulders because of their volumes. Thus, it could be expected that POMD soil would store more organic carbon than the BRC soil despite the observation that their thicknesses are similar. In summary, the combination of mineral types, rock contents, and soil thickness may lead to nonlinear weathering control of soil carbon storages.

The discussions here suggest hillsopes as an excellent platform where rapidly progressing fields of geomorphology, geochemistry, and ecology could be fruitfully combined without sacrificing the mechanistic theories of these fields.

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Figure Captions

Figure 1. LiDAR-based shade map of the study tributary basin to the Middle Fork Feather River.

Three hillslope transects were selected. Hillslopes are steeper at the lower elevations because of their proximity to the rapidly incising Middle Fork Feather River. The incision signal from Feather River has not fully propagated to the upper portion of the tributary basin. This study targets three Hillslopes. BRC is below the knickpoint. FTA is adjacent to the knickpoint, while POMD is above the knick point. Knick point is marked with bright dot.

Figure 2. (a) Soil thicknesses at the studied hillslope transects.

These soils are from convex (eroding) parts of the hillslopes. While the soil erosion rates increase by 15 folds in the order of POMD to FTA to BRC, there are significant overlaps in the observed soil thicknesses. (b) Fine size (<2mm) mass fractions. Despite the large variations, POMD soils have fine fractions that are significantly larger than in the BRC soils. There is no significant difference in the fine size fraction between POMD and FTA soils.

Figure 3. (a) Concentrations of Zr and TiO2 in soil samples. (b) Topographic trends of Zr and TiO2 abundances in POMD. The arrow indicates the trend in data toward downslope in the eroding part of the hillslope. (c) Particle sizes in the depositional soil at the POMD.

Figure 4. Relationship between soils' τ values and Saprolite' τ values.

Figure 5. The soil depth profiles of pedogenic crystalline iron oxide.

Figure 1

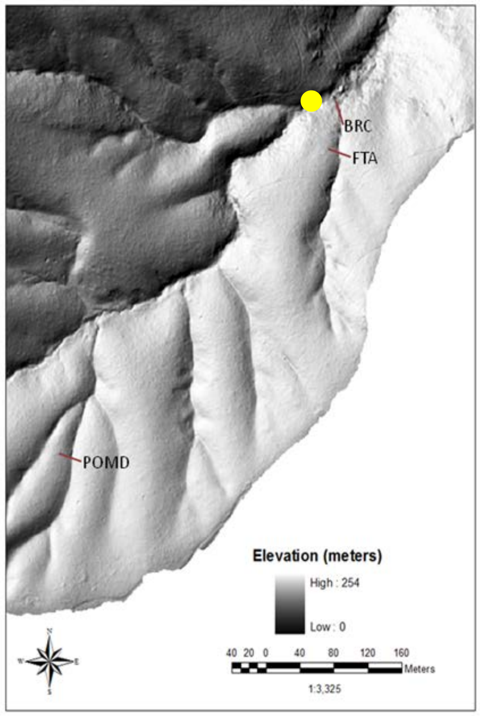

Figure 2.

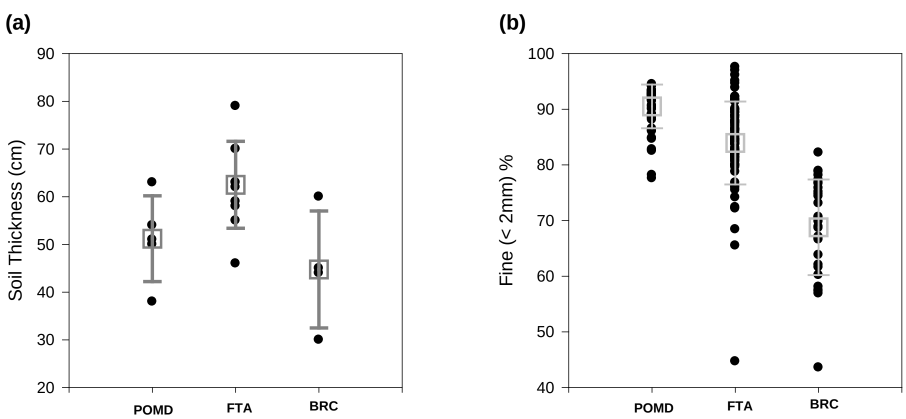

Figure 3

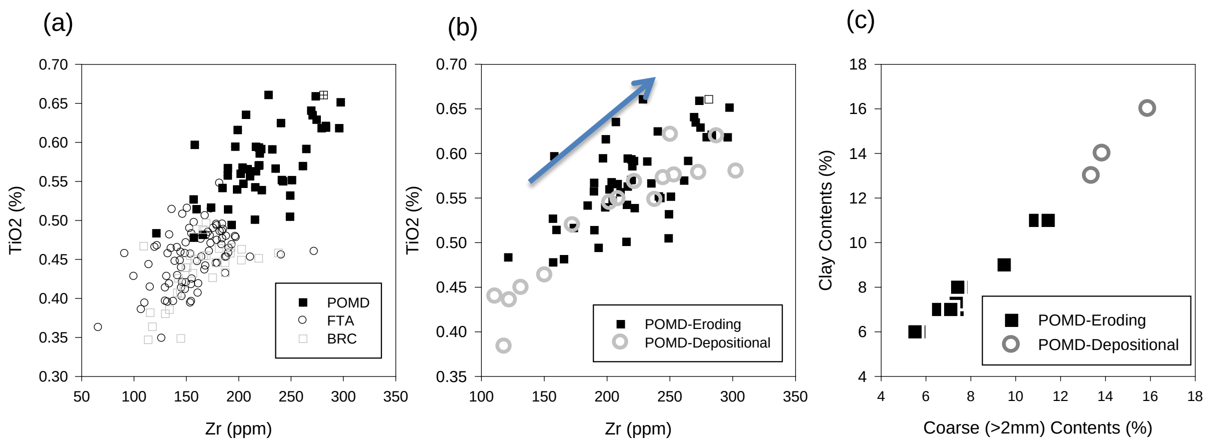

Figure 4.

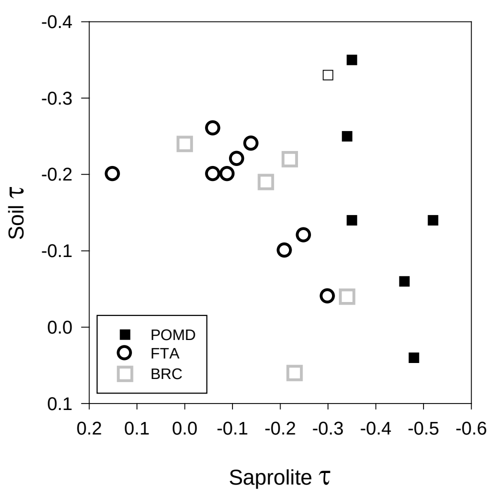

Figure 5.